Estimating climate sensitivity using a two-zone energy balance model and satellite observations

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Oerlemans J. and van den Dool, H. M. (1978). Energy balance climate models: Stability experiments with a refined albedo and updated coefficients for infrared emission. J. Atmos. Sci., *35,* 371-381.

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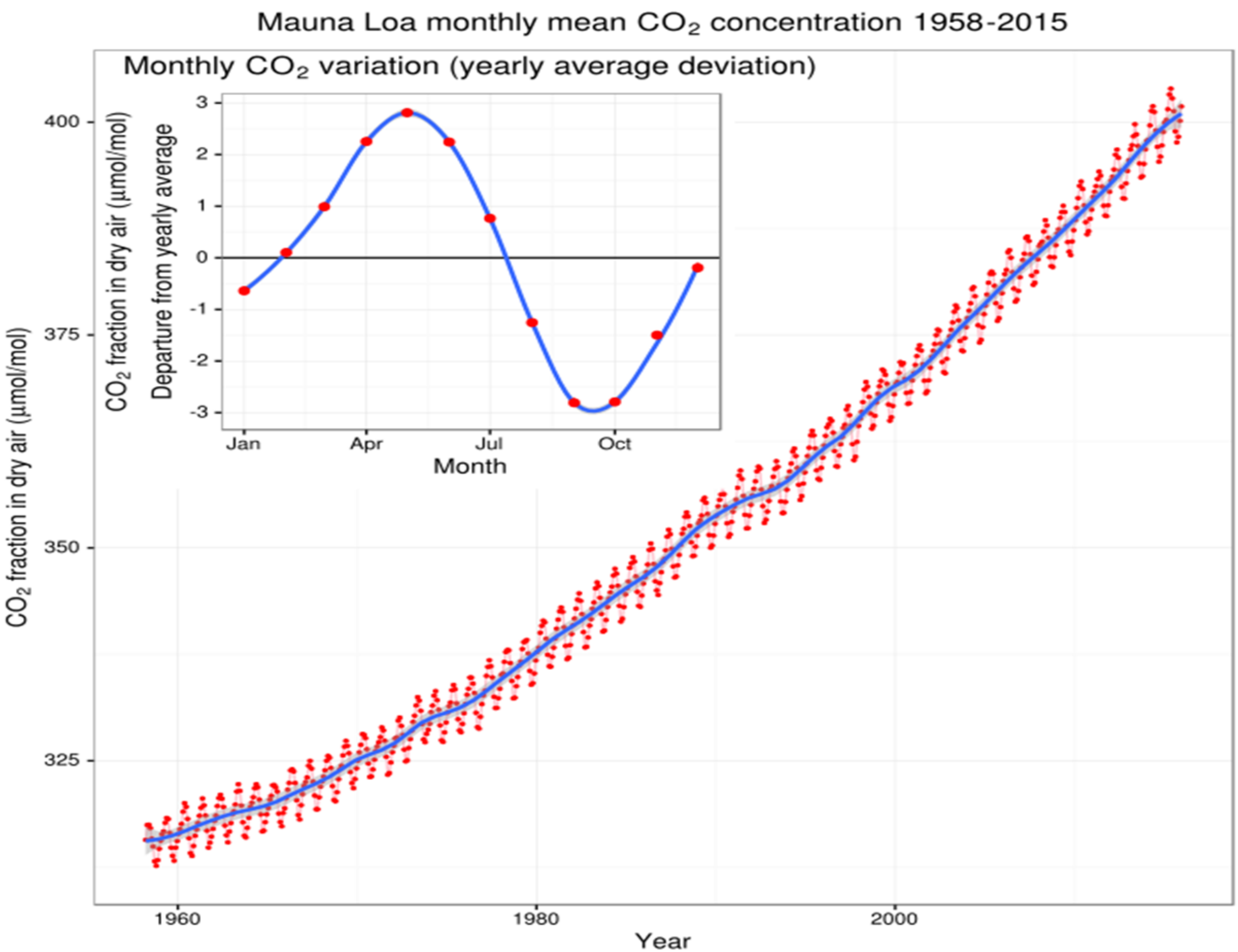
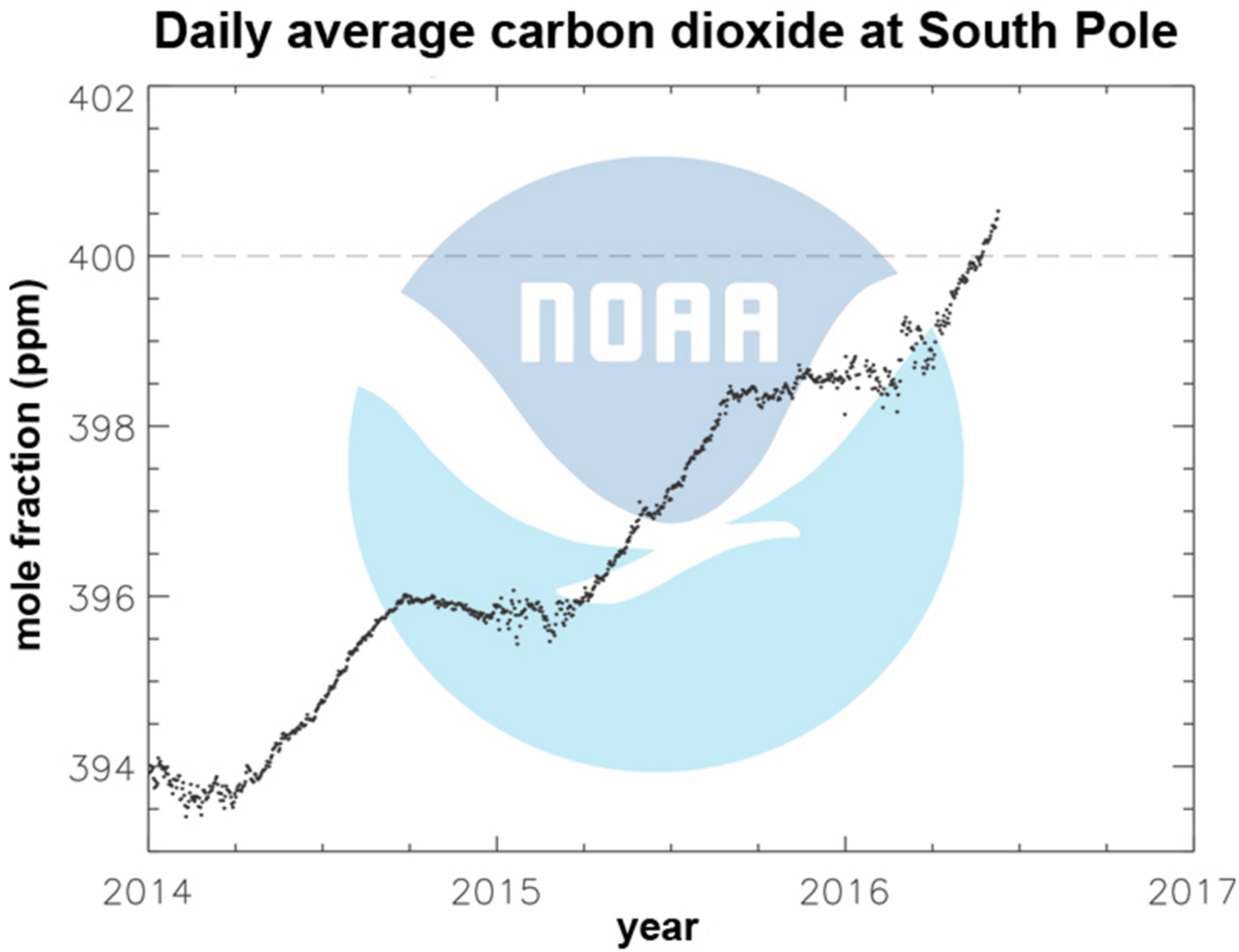


Mauna Loa monthly mean CO_2 concentration 1958-2015
Monthly CO_2 variation (yearly average deviation)
CO_2 fraction in dry air (µmol/mol)
Departure from yearly average
3
2
1
0
-1
-2
-3
Jan
Apr
Jul
Oct
Month
CO_2 fraction in dry air (µmol/mol)
400
375
350
325
1960
1980
2000
Year


Daily average carbon dioxide at South Pole
402
400
398
396
394
mole fraction (ppm)
2014
2015
2016
2017
year
NOAA

Climate sensitivity is the equilibrium (steady-state) change in the annual global-mean surface temperature (GMST) following a doubling of the atmospheric equivalent CO_2 concentration.

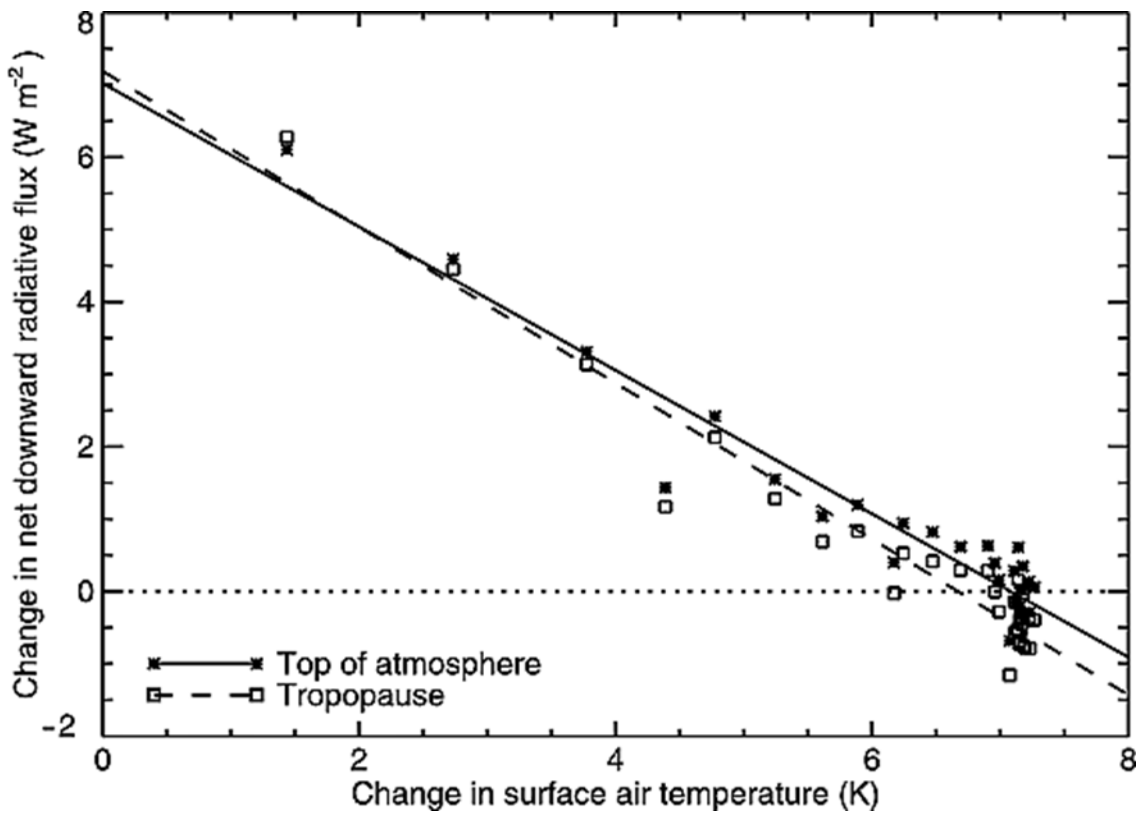
In IPCC (2013), the effective radiative forcing for a doubled CO_2 concentration is given as 3.7 W m^{-2}. This value will be adopted here; thus,

$$\Delta Q = 3.7 \text{ W } m^{-2}$$

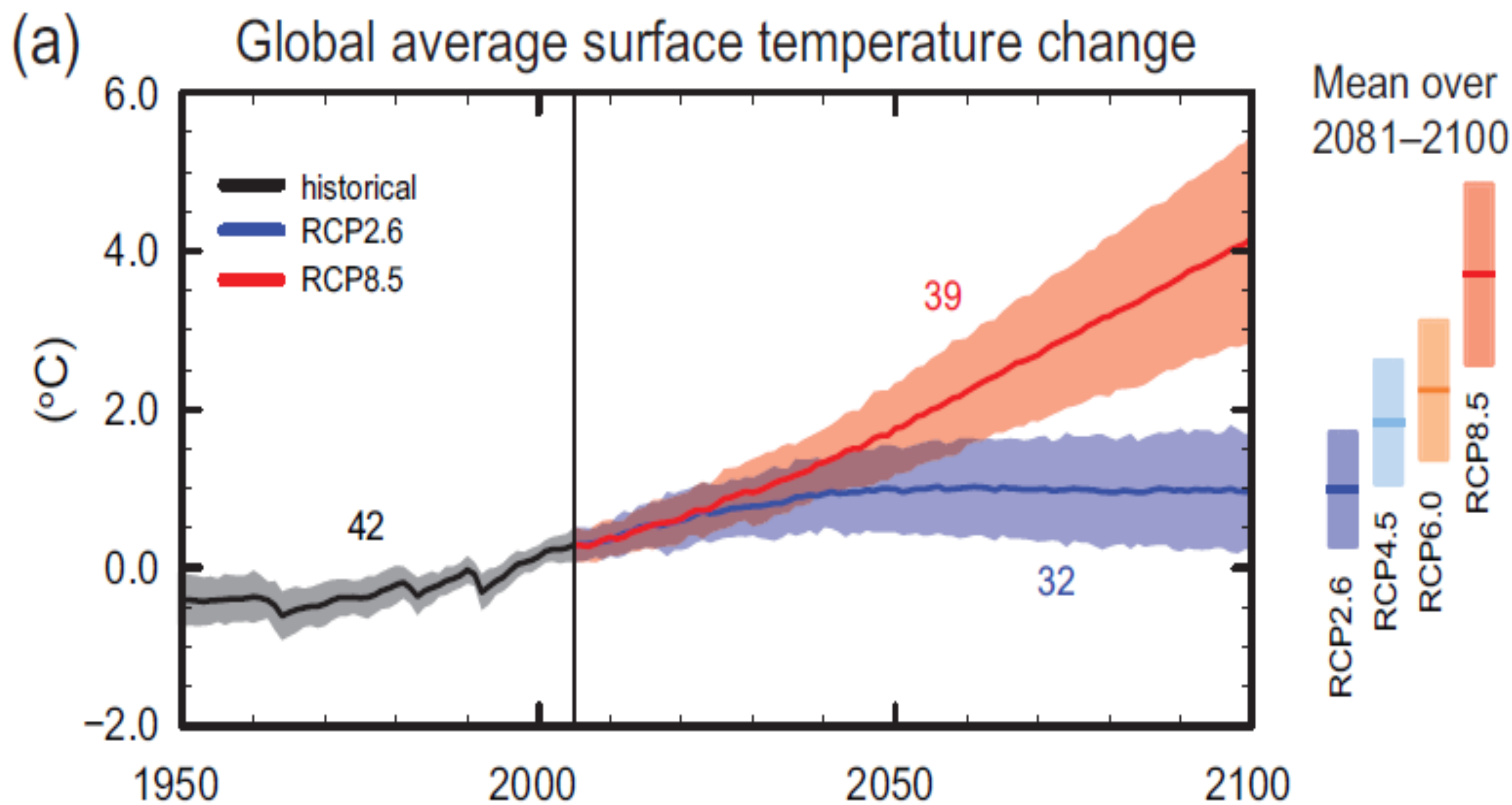
Climate sensitivity estimates

	Range	Best Estimate
Charney Report (1979)	1.5 – 4.5°C	3.0°C
IPCC AR4 (2007)	2.0 – 4.5°C	3.0°C
IPCC AR5 (2013)	1.5 – 4.5°C	None given

Estimating climate sensitivity using GCMs



Change in net downward radiative flux (W m-2)
Change in surface air temperature (K)
Top of atmosphere
Tropopause
8
6
4
2
0
-2
0
2
4
6
8



(a)
Global average surface temperature change
Mean over
2081–2100
historical
RCP2.6
RCP8.5
6.0
4.0
2.0
0.0
−2.0
(°C)
42
39
32
1950
2000
2050
2100
RCP2.6
RCP4.5
RCP6.0
RCP8.5

Water vapour feedback
(amplification of CO_2-induced warming by the resulting increase in atmospheric water vapour)
is the primary source of global warming in GCMs.

What about the real climate system?

Estimating climate sensitivity using simple energy balance models and satellite observations

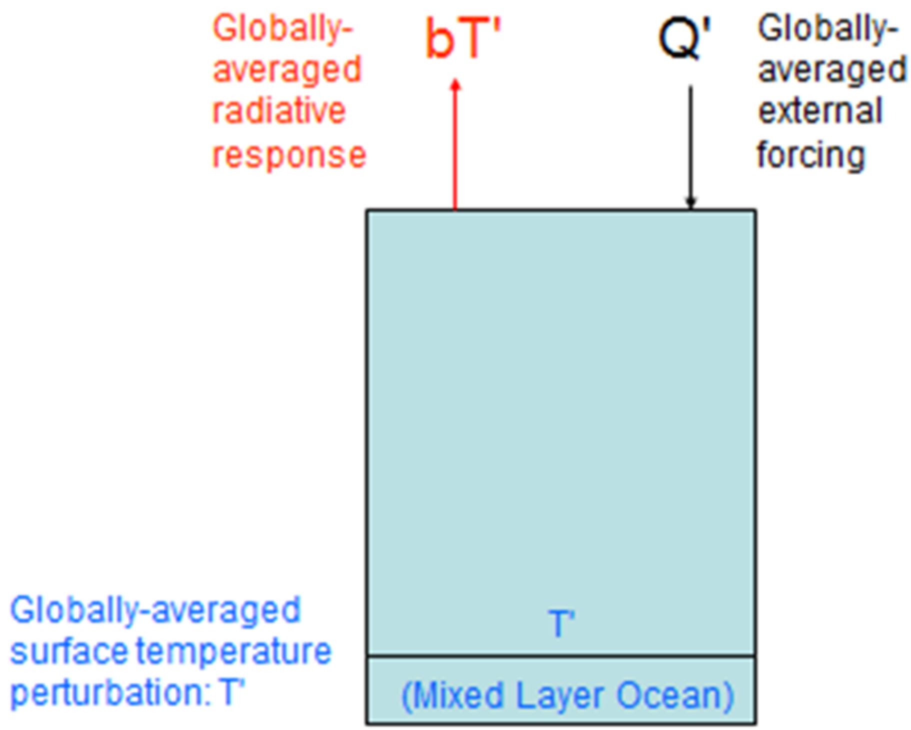
Radiative Response Coefficient (*b*):

$$b \equiv \frac{dFlux\uparrow}{dT}$$

Estimates of *b* can be obtained by linearly regressing fluctuations in upward (LW+SW) radiative flux at TOA, from observations or from non-equilibrium GCM output, against fluctuations in surface temperature.

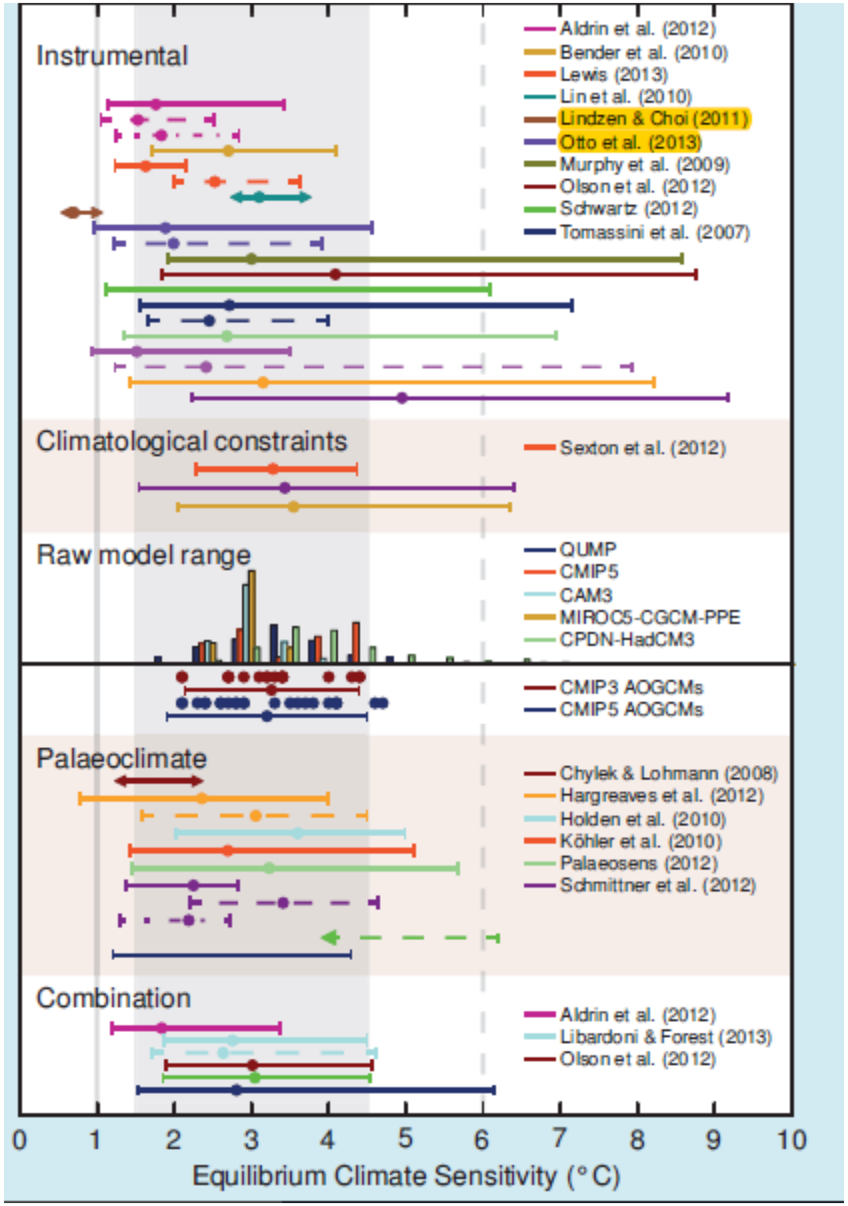
The Zero-Dimensional Energy Balance Model (ZDM)

The Zero-Dimensional Model (ZDM)



If we take b as given by satellite observations, the ZDM expression for climate sensitivity is given by Eq. (4):

$$T_{ZDM} = \frac{Q}{b}$$



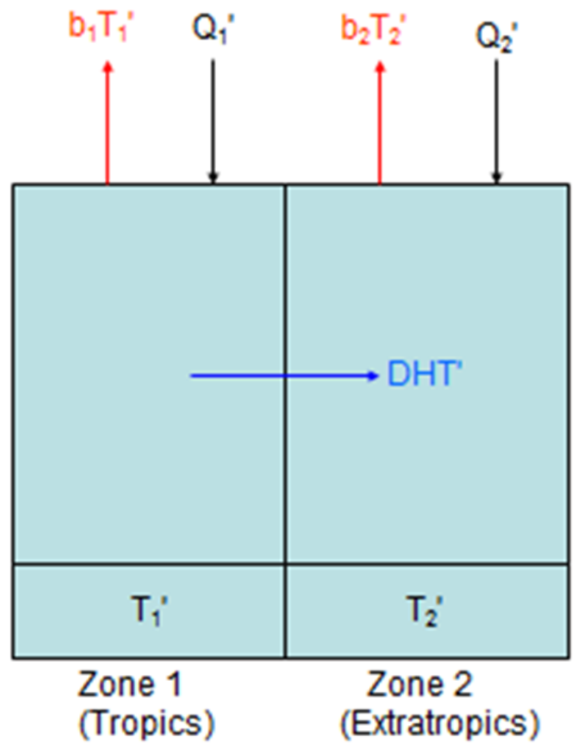
Instrumental
Aldrin et al. (2012)
Bender et al. (2010)
Lewis (2013)
Lin et al. (2010)
Lindzen & Choi (2011)
Otto et al. (2013)
Murphy et al. (2009)
Olson et al. (2012)
Schwartz (2012)
Tomassini et al. (2007)
Climatological constraints
Sexton et al. (2012)
Raw model range
QUMP
CMIP5
CAM3
MIROC5-CGCM-PPE
CPDN-HadCM3
CMIP3 AOGCMs
CMIP5 AOGCMs
Palaeoclimate
Chylek & Lohmann (2008)
Hargreaves et al. (2012)
Holden et al. (2010)
Köhler et al. (2010)
Palaeosens (2012)
Schmittner et al. (2012)
Combination
Aldrin et al. (2012)
Libardoni & Forest (2013)
Olson et al. (2012)
0
1
2
3
4
5
6
7
8
9
10
Equilibrium Climate Sensitivity (°C)

Two-zone(tropical/extratropical) Energy Balance Models

Model A (Lindzen and Choi, 2011)

Model B (Bates, 1999, 2012, 2016)

The Two-Zone Models (A and B)



Energy Equations for Model B

Primes refer to small perturbations about a basic equilibrium climate state (all quantities are running annual means evolving slowly on long time scales):

$$c_0 \frac{dT_1}{dt} = Q_1 \quad b_1 T_1 \quad d \; T_1 \quad T_2$$

$$c_0 \frac{dT_2}{dt} = Q_2 \quad b_2 T_2 + d \; T_1 \quad T_2$$

Sensitivity Analysis

The sensitivity of Model B is found by imposing a step-function forcing

$$Q_1, Q_2 \quad = \quad Q, \;\; Q\, 1(t)$$

where $Q = 3.7\ \mathrm{Wm}^{-2}$

and taking the equilibrium solution at $t =$.

Using to denote global mean increments at equilibrium,

e.g., $T = \quad T_1 + \quad T_2 \ /2 \quad t =$, it is found that

$$T_B = 1 + X \quad T_A$$

where

$$T_A = \frac{Q}{b_1 + b_2 \ /2}$$

$$X = \frac{1}{S_2} \ {\frac{b_1 \quad b_2}{2}}^{2}$$

It is seen that $X \quad 0$ and $T_B \quad T_A$ under two circumstances:

$$b_1 \quad b_2 \text{ or } d$$

Under general circumstances, X can be large and T_B and T_A can be quite different.

Parameter Values

Values of the tropical radiative response coefficient (b_1) are given by

(i) Satellite observations;
(ii) GCMs run in AMIP mode
(fixed SST);
(iii) GCMs run in CMIP mode
(SSTcalculated using a coupled ocean model)

Values taken from

Lindzen and Choi (2011)

Mauritsen and Stevens (2015)

Table 1. Linear Regression Slopes (Units: $W\,m^{-2}\,K^{-1}$) of Anomalies in Outgoing TOA Radiation (LW, SW, and LW + SW) Against Surface Temperature in the Tropics, as Determined From Observations [$(\text{Slope})_{obs}$], From AMIP GCMs [$(\text{Slope})_{AMIP}$], and From CMIP GCMs [$(\text{Slope})_{CMIP}$][a]

	$(\text{Slope})_{obs}$	$(\text{Slope})_{AMIP}$	$(\text{Slope})_{CMIP}$
LC11, LW	5.3 ± 1.3	1.8 {−0.8, 4.4}	3.0 {0.6, 5.8}
LC11, SW	1.9 ± 2.6	−2.9 {−3.8, −0.1}	1.2 {−3.3, 3.9}
LC11, LW + SW	6.9 ± 1.8	−1.1 {−4.7, 1.0}	4.2 {0.5, 8.1}
MS15, LW	4.1 ± 0.8	2.7 {0.8, 5.4}	2.2 {0.2, 4.2}
MS15, SW	−0.9 ± 0.9	−1.4 {−4.3, 1.8}	−1.2 {−4.6, 0.8}
MS15, LW + SW	3.2 ± 1.0	1.3 {−1.1, 4.7}	1.0 {−1.1, 3.0}

[a]The uncertainty interval in the first column of figures is ±1 standard error; values in curly brackets in the other columns are the outer limits of the quantity in question. The slopes of *Lindzen and Choi* [2011; LC11] are evaluated using data for the oceanic part of the latitude band (20°S–20°N), while those of *Mauritsen and Stevens* [2015; MS15] are evaluated using data for the entire latitude band (20°S–20°N).

Estimating b_2

It is difficult to estimate b_2 observationally from satellites because of the predominance of noise in surface temperatures over land.

Lindzen and Choi (2011) assumed that b_2 is given by the Planck value corresponding to the extratropical emission temperature (249 K), based on the low specific humidity and approximately unvarying 50% cloud cover in this region; this gives $b_2 = 3.5$ W m^{-2} K^{-1}.

Pierrehumbert [1995, Figure 2] has used a GCM radiation code to evaluate the clear-sky OLR as a function of low-level air temperature for various relative humidities. Choosing a low-level temperature characteristic of the extratropics (280 K) and the 75% RH curve, his calculations gives $b_2 \approx 2.1$ W m^{-2} K^{-1}.

Langen and Alexeev [2005], in aquaplanet experiments using two GCMs without an iris effect, found an extratropical LW response coefficient of approximately 2 W m^{-2} K^{-1}.

Guided by these results, b_2 is allowed to vary in the range (2.0, 3.5) W m^{-2} K^{-1}.

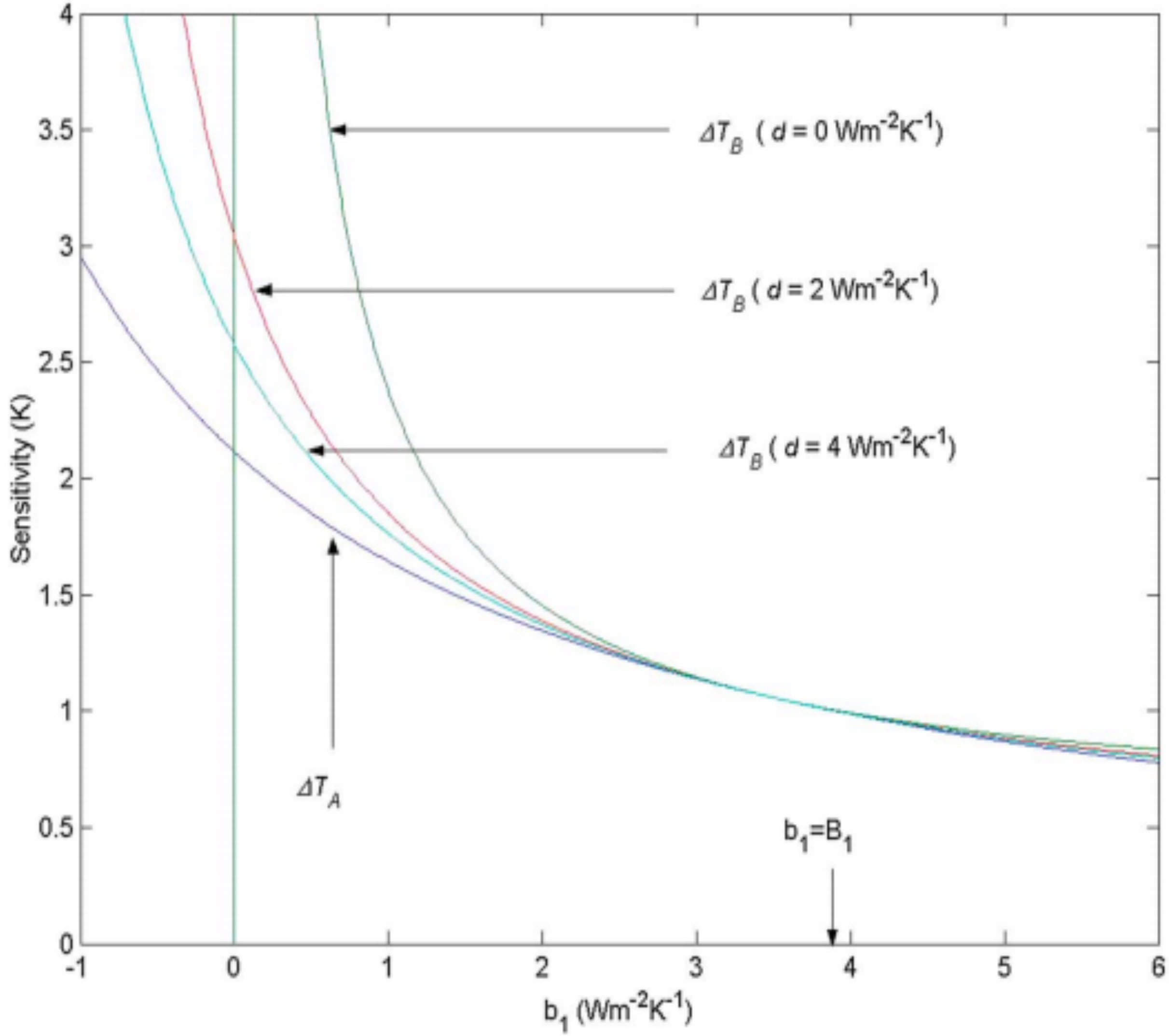
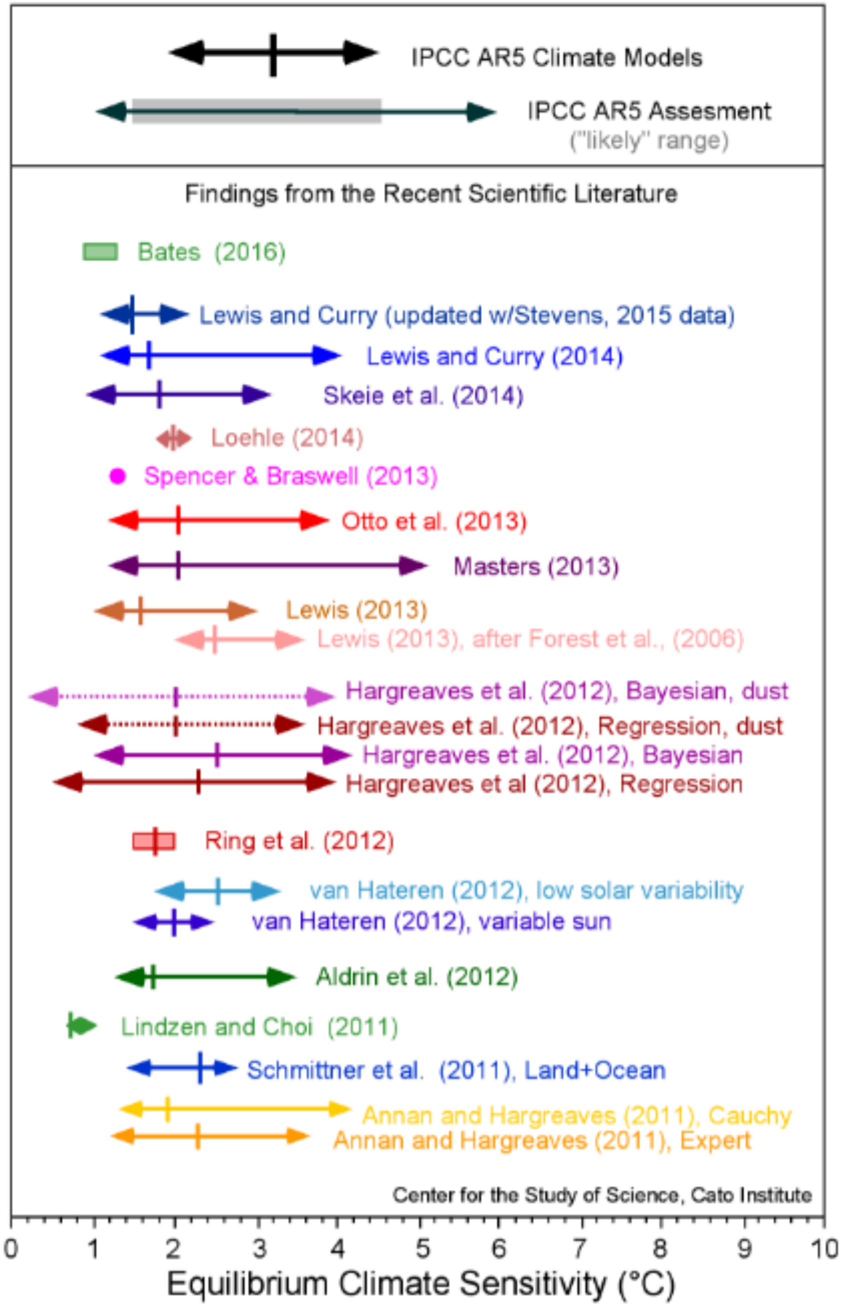


Figure 1. EfCS provided by Model A (ΔT_A) and Model B (ΔT_B) as functions of the tropical radiative response coefficient (b_1) with the extratropical radiative response coefficient (b_2) set at 3.5 W m^{-2} K^{-1} and the DHT coefficient (d) set at (0, 2, 4) W m^{-2} K^{-1}. Forcing: ΔQ = 3.7 W m^{-2}. See text for further details.

Table 2. EfCS as Given by Model B for the Mean Observational Range of b_1 and the Best Estimates of the Likely Ranges of (b_2, d)[a]

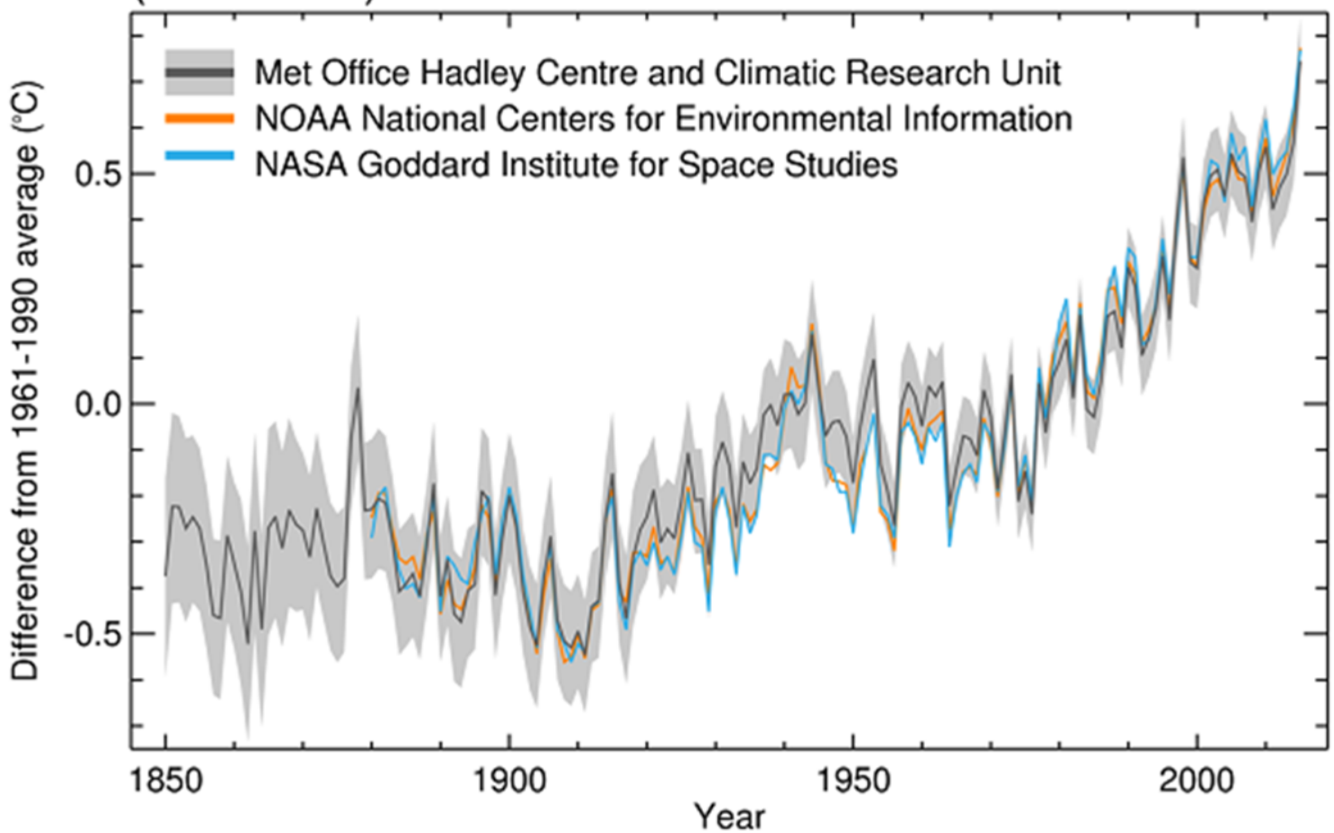
(b_1, b_2, d)	ΔT_B
(4.1, 3.5, 2.0)	0.977
(4.1, 3.5, 4.0)	0.976
(5.3, 3.5, 2.0)	0.860
(5.3, 3.5, 4.0)	0.854
(4.1, 2.0, 2.0)	1.279
(4.1, 2.0, 4.0)	1.254
(5.3, 2.0, 2.0)	1.123
(5.3, 2.0, 4.0)	1.083

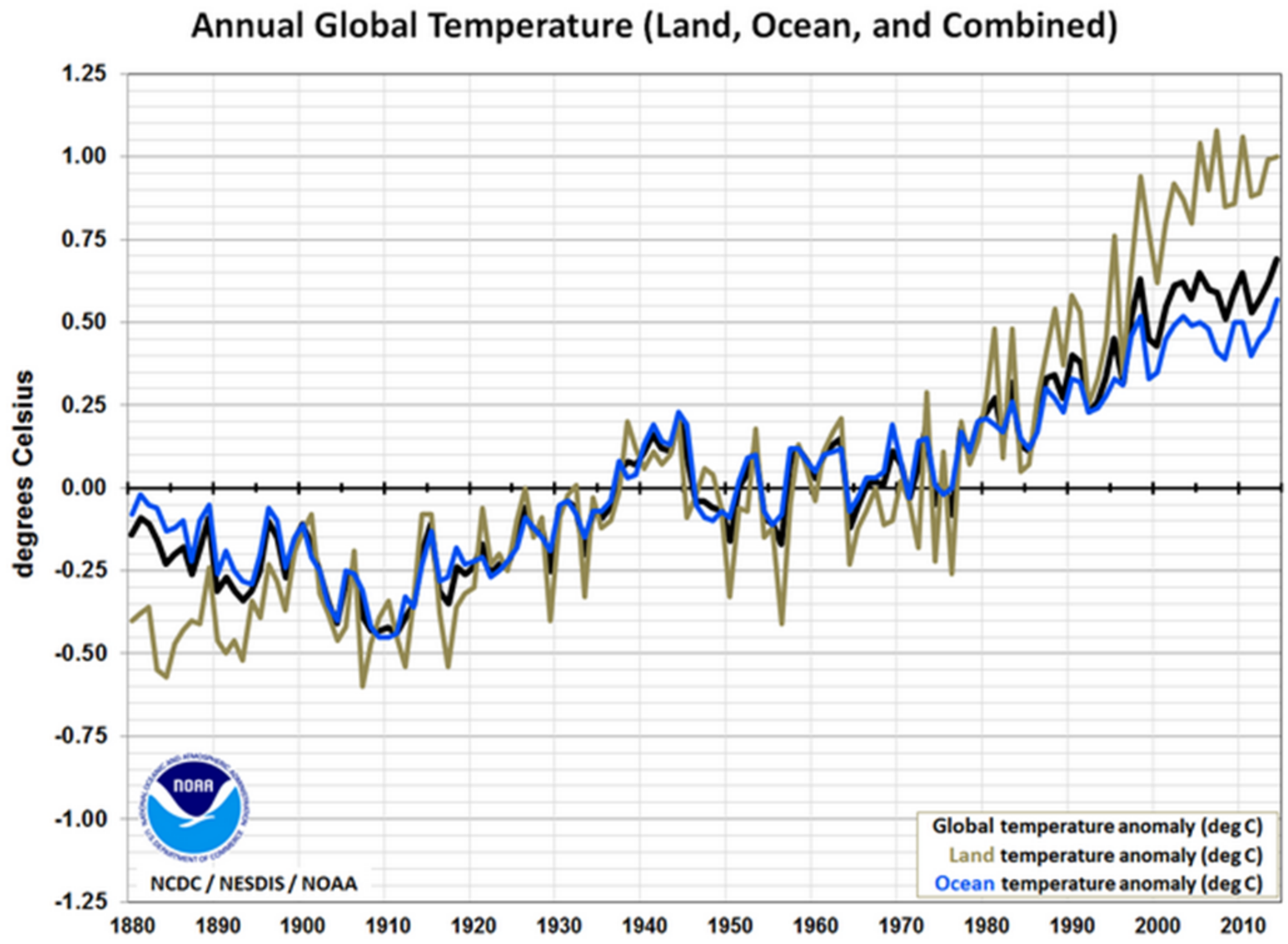
[a]Units of (b_1, b_2, d): $\mathrm{W\,m^{-2}\,K^{-1}}$. Units of ΔT_B: °C. Forcing: $\Delta Q = 3.7\ \mathrm{W\,m^{-2}}$. See text for further details.


IPCC AR5 Climate Models
IPCC AR5 Assesment
("likely" range)
Findings from the Recent Scientific Literature
Bates (2016)
Lewis and Curry (updated w/Stevens, 2015 data)
Lewis and Curry (2014)
Skeie et al. (2014)
Loehle (2014)
Spencer & Braswell (2013)
Otto et al. (2013)
Masters (2013)
Lewis (2013)
Lewis (2013), after Forest et al., (2006)
Hargreaves et al. (2012), Bayesian, dust
Hargreaves et al. (2012), Regression, dust
Hargreaves et al. (2012), Bayesian
Hargreaves et al (2012), Regression
Ring et al. (2012)
van Hateren (2012), low solar variability
van Hateren (2012), variable sun
Aldrin et al. (2012)
Lindzen and Choi (2011)
Schmittner et al. (2011), Land+Ocean
Annan and Hargreaves (2011), Cauchy
Annan and Hargreaves (2011), Expert
Center for the Study of Science, Cato Institute
0
1
2
3
4
5
6
7
8
9
10
Equilibrium Climate Sensitivity (°C)

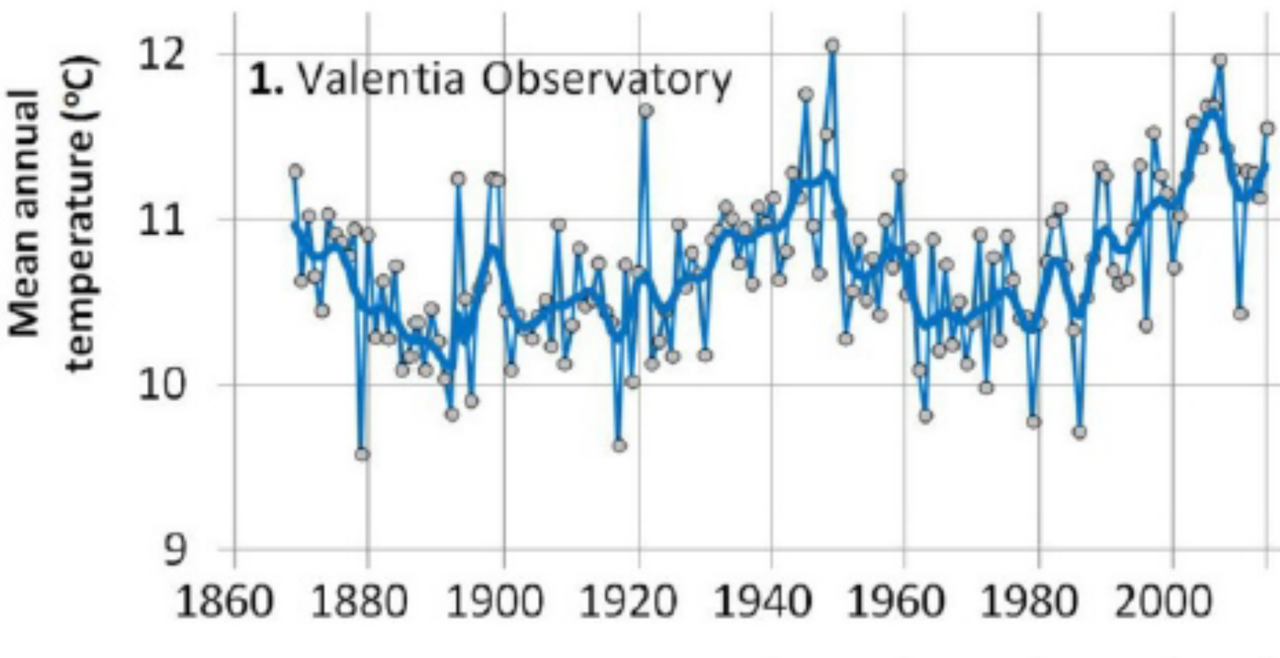
Is a climate sensitivity estimate of 1°C compatible with the observed evolution of the GMST over the period of the global instrumental record?

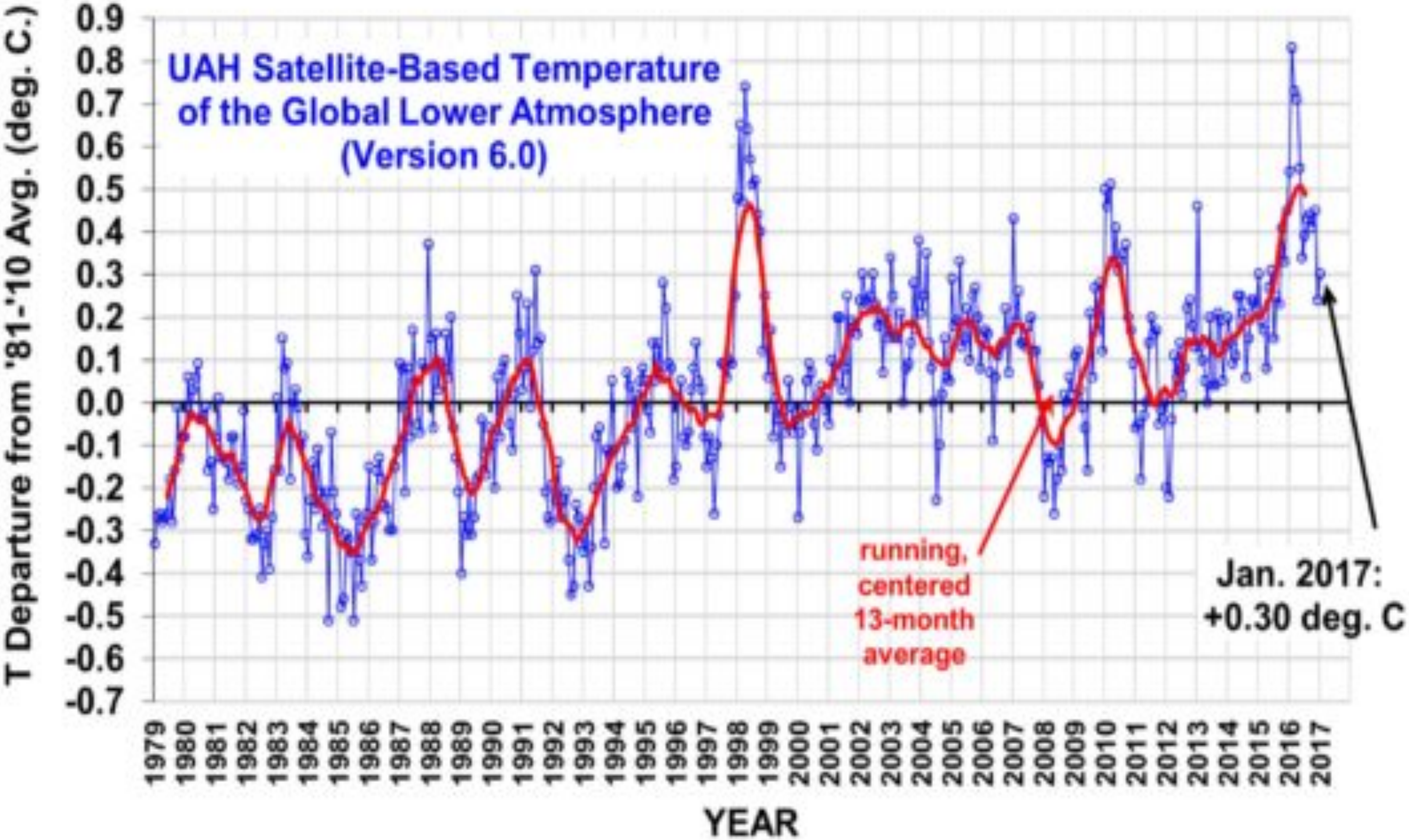
Global average temperature anomaly
(1850-2015)



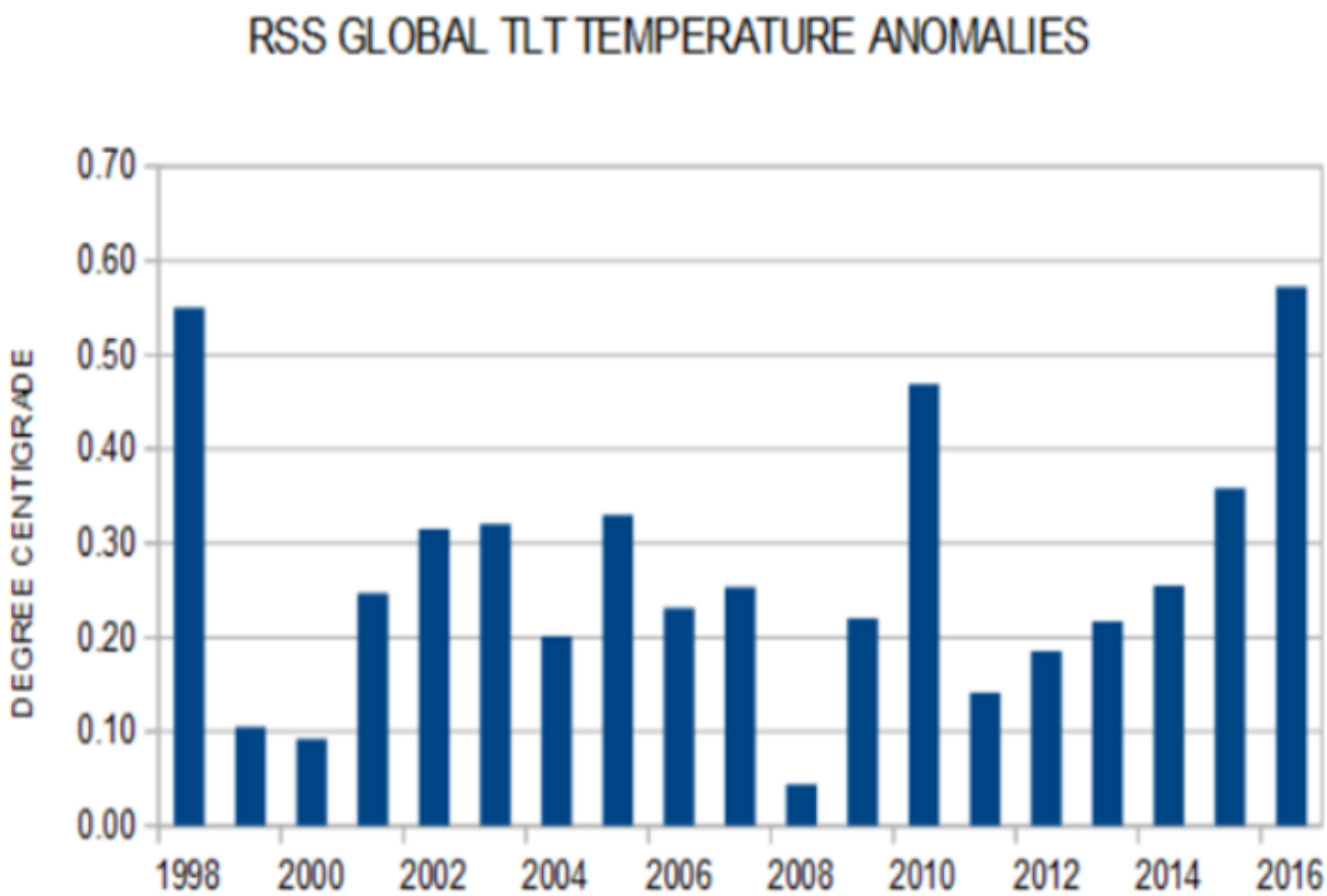


Annual Global Temperature (Land, Ocean, and Combined)
degrees Celsius
1.25
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
-1.25
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
NOAA
NCDC / NESDIS / NOAA
Global temperature anomaly (deg C)
Land temperature anomaly (deg C)
Ocean temperature anomaly (deg C)


1. Valentia Observatory
Mean annual temperature (ºC)
12
11
10
9
1860
1880
1900
1920
1940
1960
1980
2000



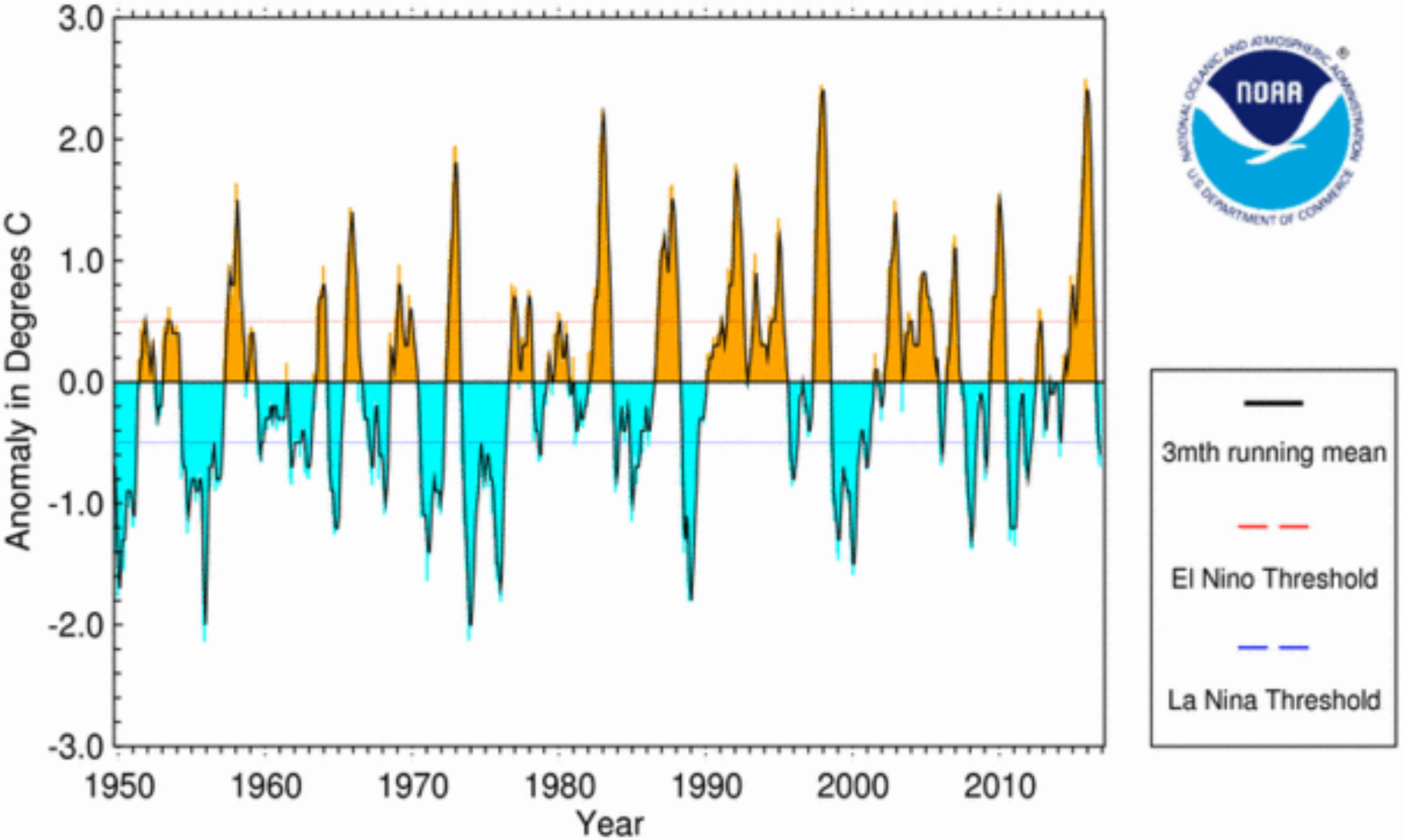
UAH Satellite-Based Temperature
of the Global Lower Atmosphere
(Version 6.0)
T Departure from '81-'10 Avg. (deg. C.)
YEAR
running, centered 13-month average
Jan. 2017: +0.30 deg. C


RSS GLOBAL TLT TEMPERATURE ANOMALIES
DEGREE CENTIGRADE
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016

How Much of the Marked Warming of 2015-2016 is due to Greenhouse Gas Increase and How Much is Due to Natural Variability?

(a) The Role of ENSO

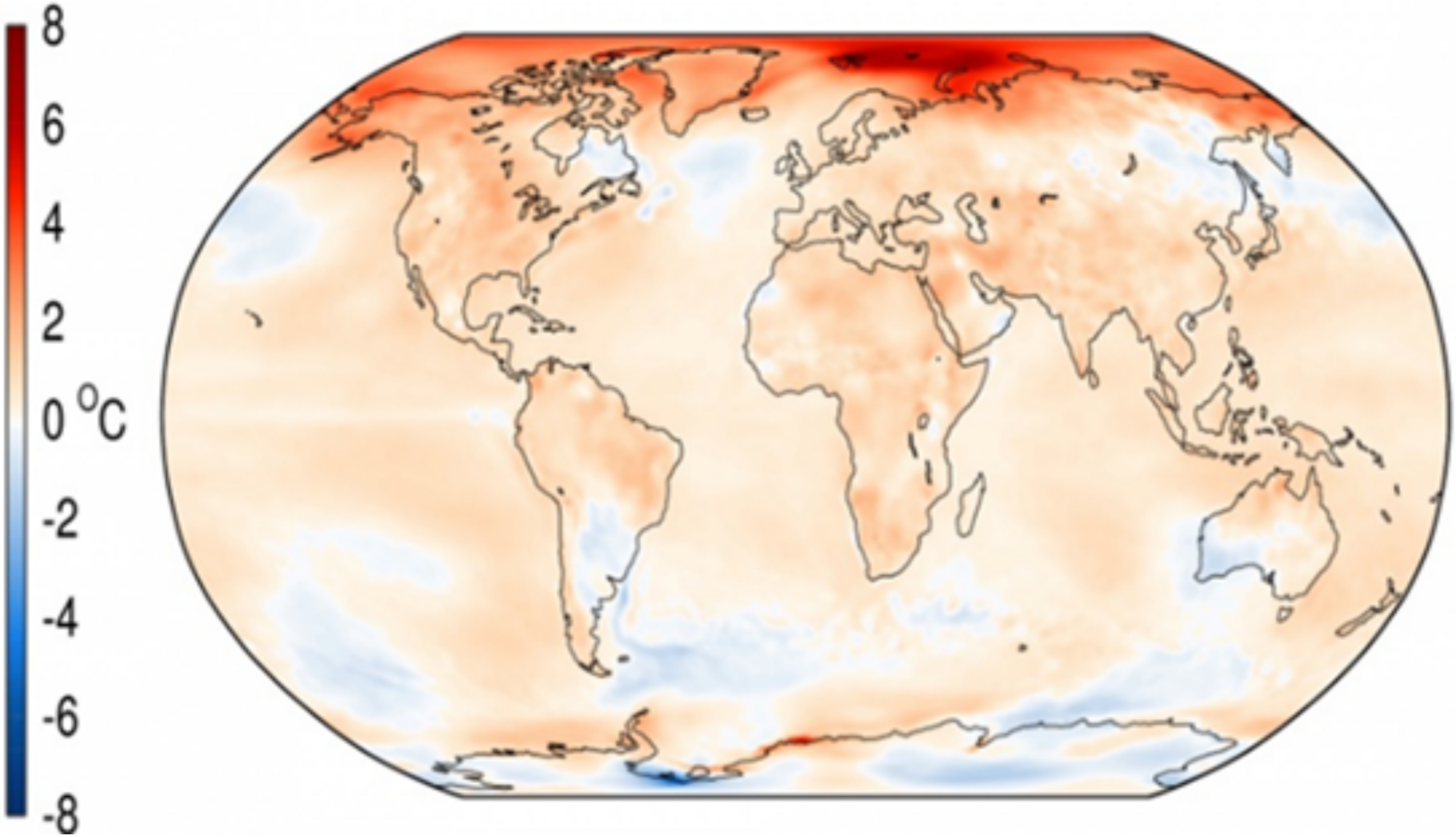
SST Anomaly in Nino 3.4 Region (5N-5S,120-170W)



National Centers for Environmental Information / NESDIS / NOAA

(b) The Current warming is much more asymmetric than is expected from the approximately symmetric CO_2 increase.

Surface air temperature anomaly for **2016** relative to the average for 1981-2010



Warming Trends in the Satellite Era 1979-2014 (°C/decade)

	Conventional surface datasets (CRUTem4 and HadSST3)	Reanalysis dataset (Cederlöf et al., 2016)	Satellite dataset (lower trop; Spencer et al., 2015)
Land	0.26 (surface)	0.25 – 0.27 (surface)	0.19 (lower trop)
Ocean	0.12 (surface)	0.06 – 0.12 (surface)	0.08 (lower trop)
Global	0.16 (surface)	0.08 – 0.11 (mid. trop)	0.11 (lower trop)

Cederlöf et al. (2016): The mid-tropospheric trend is similar over land and ocean. It agrees closely with the ocean surface trend. A land surface trend substantially in excess of the mid-tropospheric trend, as above, is suggestive of a problem with the land surface temperatures.
Cederlöf et al. strongly suggest using tropospheric temperature trends from reanalyses in climate sensitivity studies.

Conclusions

1) A two-zone (tropical/extratropical) energy balance model of the climate system that includes inter-zone energy transport has been constructed and its properties examined.

2) Satellite observations indicate that in the tropics the real climate system is radiatively more stable (i.e., emits more energy to space for a given surface temperature increase) than is indicated by the GCMs.

3) Inserting the observed value of the tropical radiative response coefficient and the best estimates of the other parameters into the two-zone model gives a climate sensitivity of ~ 1°C.

4) This value of climate sensitivity is not inconsistent with the observed global temperature record.

References

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Bates, J.R. (2012). Climate stability and sensitivity in some simple conceptual models. *Clim. Dyn*., **38**, 455-473. DOI 10.1007/s00382-010-0966-0.

Cederlöf, M, Bengtsson, L. and Hodges, K. (2016). Assessing atmospheric temperature data sets for climate studies. *Tellus A*, **68**, 31503, http://dx.doi.org/10.3402/tellusa.v68.31503

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The End